Assessment Study of *ATHLET12A* Based on the KS Facility in Kurchatov Institute Stop Fill Problem for RBMK

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1. Introduction

This report was prepared in the frame of scientific Russian-German co-operation in verification and adaptation of the code ATHLET for RBMK reactor. The work described in the report was fulfilled in the following directions:

- Experimental data analysis
- Development of the input data deck for KS facility
- Performing of the verification calculation
- Optimization of the KS facility input data deck for code ATHLET
- Discussion of the results

The KS „stop of flow“ expirements belong to the set of tests, wich are suitable for evaluation of the design-basis RBMK accidents. These experiments present the data on the thermal-hydraulic processes that occur at an abrupt flow stoppage under low thermal loads (after the scram of reactor power) and were used for the ATHLET verification for the following specific RBMK LOCA phenomena:

1. Depletion of the fuel channel and deterioration of the heat transfer
2. DNB or dry out of the fuel assembly
3. Counter current steam and water flow in the fuel channel and steam-water tubes
4. CCFL

This work is the second post-test attempt to simulate the "stop flow" KS experiments with ATHLET. The first one was performed about 8 years before and was based on original KS reports and unfortunately practically failed because it became clear that the rate of uncertainties and ambiguity of that description of facility, instrumentation and test scenario. It is worth mentioning that at that time experiments and their descriptions were prepared not for the thermal hydraulic code verification and validation. But when this problem was risen, the set of previously fulfilled experiments and those with suitable quality and completeness were revised, new reports with additional details, better preciseness of data were issued. This was the reason why we decided to repeat simulations.

The code version used in the presented calculations was ATHLET Mod 1.2 Cycle A /2/.

2. KS Test Facility Description

KS facility is shown in Figure 2-1. The KS circuit simulates all main structural elements of the RBMK reactor. This includes:

- inlet pressure header (1),
- group distribution header (2),
- lower water communication lines (3) with an isolating control valve (4),
- fuel channel (5) with an electrically heated fuel assembly (6),
- riser (7) with a shield plug assembly (8) (sometimes this part is referred to as a lifting path),
- steam-water communication (SWC) (9).

Important difference between the facility and the prototype reactor (which is to be discussed in details later on in section 5 is the absence of the metallic tube ∅80 of fuel channel. The talkohloride insulation surrounded by the steel tube of larger diameter represents the RBMK system: tube-graphite block. By this, the primary coolant could fill the openings between the talkohloride rings and the outer tube, waiting to be spilled inside the channel.

Only the experimental section of KS facility starting at the pressure header (1) and up to the vertical separators (11) is of interest to this evaluation, and so the remaining sections of the KS facility are not described here. A more detailed description of the facility can be obtained in /1/.

3. Test Description

A series of stop flow experiments were performed to simulate the design-basis accident of an abrupt flow stoppage under low thermal loads. Nine of these experiments were chosen for evaluation with the code ATHLET. Initial conditions for nine experiments are presented in table 3-1. In each experiment the inlet control valve was closed to initiate the test, terminating flow to the channel. After flow stoppage, liquid in the heater region begins to boil-off slowly. For the lower power experiments (below 200kW), liquid drain-back from the upper SWC and lifting path acts to replenish the liquid boil-off, delaying the onset of dryout until the lifting path has drained of liquid. For the higher power experiments, liquid drain-back in insufficient to prevent dryout from occurring before the lifting path has drained.

Table 3-1 KS Facility Initial Conditions

No.	Experiment	Electrical power of fuel assembly model, kW	Pressure at inlet of fuel assembly, P16, MPa	Water temperature at inlet of fuel channel, TF1, K	Water flow rate at inlet GL, kg/s
1	SF-96	96.2	4.72	515	0.583
2	SF-108	108.1	6.78	539	0.525
3	SF-128	128.6	6.78	537	0.516
4	SF-155	155.0	6.59	537	0.539
5	SF-161	161.0	4.91	514	0.583
6	SF-201	201.0	7.52	532	0.525
7	SF-202	201.5	5.12	507	0.566
8	SF-251	251.0	7.86	538	0.533
9	SF-257	257.0	5.19	515	0.564

The inlet control valve closure time is 5s. The time between complete stoppage of flow at the inlet of the fuel channel (FC) and dryout is much greater than the closure time of the inlet control valve for each of the experiments. Therefore, the law of flow decrease at the inlet of the FC (to zero flow) was assumed to be linear. The experimental pressure in separators remained comparatively stable during each transient due to the manual throttling action of multipurpose valves between separators and condensers.

3.1. Discussion of Data

There are conventionally 3 types of experiments:

- Low power experiments (SF-96 through SF-128), which clearly show that a quasi-equilibrium mass balance is reached in the heater bundle shortly after flow stoppage (the boil-off rate is balanced by liquid drain-back). This indicates that counter-current flow from the lifting path to the heater bundle is not severely restricted (i.e. no CCFL).
- Average power experiments (SF-155 and SF-161), that show a slight, immediate decrease in mass inventory in the heater bundle (ΔP16-4) after flow stoppage.
- High power experiments (SF-201 through SF-257), which show a more pronounced immediate decrease in mass inventory in the heater bundle after flow stoppage. Thus, if CCFL is occurring at the heater bundle exit, then it must be triggered at, or near, the power levels of SF-155 and SF-161. However, it is still possible that normal friction and inter-phase drag are restricting the liquid drain-back.

Three experiments which fully represent all aforementioned types were used in the analyses: SF-108, SF-155, SF-251.

4. ATHLET Input Data Deck for KS Test facility

The model of test facility KS-RBMK is presented as a single loop in nodalization scheme, which is shown in figure 4-1. The model simulates the KS facility from the lower water communications to the separators. The whole basic one-channel model of test facility (Fig. 4-1) consists of 15 thermofluid objects (TFO) and 16 heat conduction objects (HCO). That covers 101 nodes (control volumes, CV) with 107 junctions and 108 heat conduction volumes (HCV). Nodalization of objects (i.e. coordinates of CV boundaries) was chosen according to ATHLET manual and with regard to locations of transducers. Calculated results at these locations in the model were then compared with the corresponding measured data. The data concerning the rod temperatures was used rather for the detecting of the onset of dry out. So the main measured data was the ΔP behaviour in various parts of the test facility.

4.1. Scenario

Calculations began without heat losses and zero heat (rod) power at each run. After 50 seconds the power was switched on and after 100 seconds heat losses were on too. Then after 1000 s the steady state conditions were reached. At this moment the transient calculation started, so the end of first 1000s of each calculation corresponds to zero time of transient, also in pictures. Thus, at the zero moment (on plots) the inlet valve started to close and after 5 seconds was fully closed. The duration of transient was different in each experiment. The sharp raise of any rod temperature determined the end of experiments.

5. Results of ATHLET Calculations

The initial development of methodology of input model tune up was rather important. The individual sets of options, choice of nodalization etc. for the every experimental condition could make it possible to reach good agreement with measured data. But this work has no sense from the standpoint of the general goals of ATHLET verification for the processes with the deterioration of coolant flow in RBMK core.

So, the whole analyses was split into two parts:

1. preparation of "well tuned up" input deck for the chosen single experiment, all uncertainties of experiments and facility description were taken into account during this work
2. calculations of the rest of experiments in the series with the "frozen" input deck

Variations of "numbers and options" in input deck were allowed only at the first stage of calculations. Then the frozen input deck was regarded as "good" only in case when reasonable results could be obtained with this deck against other experiments in the series.

Experiment "SF-108" was taken as a working experiment for the primary work with the input deck. The KS personnel defined this experiment as the most reliable in all the measurements (the errors were even lower than declared in report /1/). As it was mentioned the main data was the ΔP distribution, the cladding temperatures were taken into account too. To improve steady state results the local pressure drop coefficients were varied (fine-tuning) around the given in /1/ values.

Then in a series of transient runs experimental and calculated results were analyzed further. For the better understanding of the nature of discrepancies between these results additional thermal-hydraulic parameters in various locations (such as void fraction, phase velocities and integral flowrates) were investigated. The sensitivity analyses of the input model was performed too. As a result, three basic variants of input models were worked out. The first one is represented in the Figure 4-1, this is the simplest one-channel model. The above mentioned two-channel model was obtained from the one-channel model by introducing the inner "hot" and outer "cold" areas of heated part. The third and the best scheme was also obtained from the one-channel model by adding the parallel thin channel standing for the openings between the insulator rings and the outer steel tube. These three schemes were used for simulation of the main experiments that represent main phenomena of the "stop of flow" regimes: SF-108, SF-155, SF-251.

5.1 Basic issues

1) <u>Geometry</u>

During the work with KS drawings some geometrical unsertainties and descrepancies were found. For example the length of the horizontal nipple at the outlet of the FC and the distance between the pressure transducers P3 and P2 were omitted. The length of the riser 'RT1' had different values in different KS drawings. The set of experiments under cosideration was conditioned by low residual heating (108 – 251 kW) and low integral flowrate. Hydrostatic component (i.e. the weight of the water column) played the main role in forming ΔP. That's why this problem was rather important for the investigations.

2) <u>Initial & Boundary conditions</u>

Every experiment had its own unique initial conditions, but the boundary conditions were generally the same for all of them. The heat transfer coefficient for the heat flux from walls to air ($k=6.0W/m^2$) was chosen iteratively to match the measured losses of 52 kW. Initial conditions were defined in the block of GCSM signals.

3) <u>Nodalization</u>

Nodalization of thermal-fluid objects was performed so to get the coordinates of pressure transducers at the center of corresponding CV. Other formal requirements of the code developers were met too. Besides, uncertainty analyses revealed that the common practise of the upper part of RBMK FC representation by one large vertical CV with side connection to the outer steam-water communication could not cope with the peculiarities of the two-phase degraded flow. This way of nodalization skips information about the dead end of the upper part of FC and is too rough in description of the connection between FC and steam-water communication. Comparison with the experimental data of the ΔP in this part was erroneous all the time (Fig. 5.3-1). Consequently, the void fraction or drift predictions were wrong. The right nodalization involves 2-chain description with the detached description of the vertical dead-end CV above the side connection (Fig. 5.3-2).

It is fair to say that the common nodalization appeared to sort well with the transient regimes of RBMK. But this is not so in case of flow deterioration and stagnant conditions. Based on the calculations performed we can advice to use our a bit more complicated noding scheme.

4) Drift options

The main difficulty of obtaining satisfactory calculations for experiments SF-108 and SF-155 was too sharp and steep decrease of predicted ΔP, the critical heat fluxes in the core were obtained much earlear as well. In other words, FC experienced coolant starvation and unrealistically high void fractions in calculations. One of the possible reasons could be the higher rate of liquid carry over (or simply – liquid squeezing) by steam. And consequential make up of FC from above by reversed liquid flow could also be essentially lower. To enhance the quality of calculations all available drift options were tested and as it was already mentioned 5- and 6-balance equation models were used.

It was determined that the best (but still not satisfactory) result was achieved with the 6-equation model in all TFO's above FC. At the same time the 5-equation model with "drift for bundle" option was used in the object 'HT', that represented FC. Other variants of modeling led to aforesaid drop of ΔP at first seconds of transient. Results of calculations with the DRIFT option for the round channels (parameter JDRIFT=11) are shown in Figures 5.4-1, 5.4-2 and 5.4-3, where Fig. 5.4-1 reports the effect of implementation of the model for flow regimes with bubble, churn-turbulent/slug flow in heated channel (IBUBO=+1), Fig. 5.4-2 – Viecenz correlation (IBUBO=13), Fig. 5.4-3 – Wilson correlation (IBUBO=14). This is also reported in Table 5.1. But by the end of investigations it became clear that the right choice of only these options could not recover the quality of prediction.

The rate of "the best drift choice" insufficiency could be illustrated by the following. The problem of too high void fraction in fuel channel (which led to increased losses of the amount of liquid in the FC and all associated problems) was known from the first runs. Tuning up the drift option seemed to be the natural medicine to recover it. So historically it was the first attempt to enhance ATHLET predictions. When the best drift option was obtained and the corresponding trends of ΔP in FC were clarified the rest of calculations were performed with this option. The second "treatment" we prescribed was unphysical but helpful to evaluate how far we were from the measured values. We increased heat losses from the experimental part of KS facility used in the series "Stop of flow" from feeding pipe to steam line. Conditions on the outer walls of facility were uniform (that was clarified during very fruitful discussions with KS people) so the heat transfer coefficient to the air was changed proportionally in all parts of the ATHLET input model. The result was just discouraging – appropriate heat losses sufficient to condense the extra steam in FC (to reach measured ΔP) was twice higher than that estimated in /1/ and was all in all about 100w, so practically no steam reached the steam line. This value should be increased individually in each experiment that directly testified against heat losses as a possible reason for enhancement.

5) Stop-valve operation

Another way of improving ATHLET results was to "play" with the closing function of the inlet control valve. The KS description /1/ mentioned the linear closure. Non-linear closing was considered in series of calculations to "enlarge" the water input at first seconds. But results of these calculations did not show any visible positive effect, particularly in improvement of ΔP curves. That is quite natural because of short time of closing (5 seconds) which is much smaller than the characteristic duration of processes.

6) Pressure behaviour in separator

The KS report /1/ describes the way of pressure maintenance in system as keeping the pressure in separator constant by manual operation of the discharge throttle valve in steam lines. But it is clear that at the beginning of transient the rate of steam generation grows essentially (approximately by one third due to vanishing of the subcooled factor of water in low part of the FC). This inevitably leads to some increase of system pressure unless operator detects this raise and opens the valve. Anyway, it is hardly possible to maintain the pressure absolutely constant. That’s why an assumption was made about the pressure growth (not more than 3 bars, otherwise this would be reflected in /1/) during first period of transient. To test the influence of this growth (leading to the possible additional steam condensation in FC and consequential reduction of void fraction) corresponding runs were performed for the case of SF-108 experiment. This yielded small and non-sufficient but positive effect. It is quite clear when compared with calculation with constant pressure in separator (Figures 5.6-1 and 5.6-2).

7) Evaluation of the KS data uncertainties

There is a horizontal part (lacking data concerning its length, cross section, and pressure loss coefficients) between the FC and the riser. To clarify the effect of this uncertainty various "realistic" parameters were applied to this part in number of calculations. In addition, restricted variations of FC hydraulic diameter together with FC cross-area (within preciseness of drawings and technological margins). But as in previous case effect of these uncertainties appeared to be small.

8) Two channel scheme

Two-channel model of FC with description of the internal part of assemble and the outer annular channel with thicker rods was chosen to simulate the fine peculiarities of facility (difference in cladding thickness and heat release in radial direction and the heat flux towards the insulator). This was done to check our hypothesis about the possibility of internal circulation inside the FC: liquid film flows downward along the cool surface of insulator while two-phase mixture flows upward in the core of the channel. Calculations showed such a circulation to establish during first seconds of experiments SF-108 and SF-155. This was fruitful for the small-power experiment, for example in case of SF-108 the ΔP curves (the point is ΔP in FC) came up close to the experimental ones in a distance of the measurement uncertainties. But for the higher powers that did not work: in case of SF-155 this raise of ΔP curves was not sufficient (see comparison of similar conditions calculated by 1-channel and 2-channel schemes in figures 5.9-1 and 5.9-2 respectively), and for SF-251 (i.e. 251w) there was no enhancement in comparison to the one-channel calculations. This could be explained by high drag forces of steam in range of high powers. Anyway, that could not help to get good prediction of phenomena.

9) Single FC channel with additional parallel channel

KS FC channel consists of steel tube inside which the talkohloride annular bushings are inserted as thermal isolator. Talkohloride is a solid unshrinking material (a stone) and to insert it a technological clearances with the steel tube are needed. There is no encapsulation of talkohloride bushings, so all the clearances should be inevitable filled with water prior to the transient. Before the FC voiding this liquid should be in quiescence like in U-tube system, or least in slow movement. Because of long exposure near the cold outer tube the temperature of this liquid should be essentially lower than that inside of FC. When the liquid phase in FC escapes this balance should be distorted, and this subcooled liquid would be spilled inside the FC. The main question concerning this effect is addressed to the amount of this liquid (i.e. the void space between the insulator and the steel tube) and its temperature. The problem is whether this liquid could play any significant role or not.

KS drawings report no gap between the tube and the insulator. But this fact should not mislead us, because these drawing were prepared for the thermal-hydraulic exercises with system codes and do not reflect all the technological aspects of KS facility. In this connection the experience of the former work with calculations of the KSB facility "stop of flow" experiments is just to the point. The KSB facility was constructed as the smaller analog of the KS facility and possesses the same drawbacks in concerning the structure of FC: absence of real RBMK channel tube, talkohloride rings as insulation and outer steel tube. Post-test calculations (with RELAP5 code) also showed the lack of initial amount of liquid in heated channel of KSB rig. But contrary to KS series of experiment we managed to estimate the volume of the gap between the insulator and the tube during the montage of internal KSB installations. The gap was elliptical with average size about 0.7 – 1.0 mm, the same value was chosen for the KS model. In this model the addition object 'VOR' parallel to 'H-TUBE' was introduced, variations of initial liquid temperature and its volume were performed to assess the effect and to evaluate the applicability of this assumption to all KS experiments. The uncertainty analyses showed that at the equivalent size of the gap 0.1mm the effect of the spilled liquid is negligible. The changes in initial values of water temperature could be translated in terms of the size of the gap or mass of spilled water because it is mainly a question of power transferred for heating up filled in subcooled water, but not for steam generation. The calculations presented in this report (Fig. 5.10-1 ÷ 5.10-6) depict the case with 1.0mm gap and the initial temperature 150^{o}C. What was most important – these values helped to get an exact prediction of the hydraulic situation in all investigated experiments.

10) Critical heat flux correlations

All possible options of the critical heat flux calculation were tested. Hench-Levy, Israel-Casterline-Matzner, and Biasi correlation are known to be most close to RBMK-1000 and RBMK-1500 correlations, so they were used in analyzed KS experiments. But the peculiarity of the voiding phenomena implied rather fast change of parameters in marginal transition area, so the used correlations (all of them) predicted the onset of the dry out (in other words – sharp raise of cladding temperatures) at the same time.

6. Conclusions

Concluding the work, we should emphasize significant role of the thorough and fine modeling of the RBMK FC for obtaining realistic prediction of the heated channel voiding.

As a result of the performed verification of the ATHLET code for the RBMK FC voiding phenomena against KS series of experiments "stop of flow" we can state:

1) ATHLET was able to predict hydraulic behavior of the heated channel with fuel assembly together with the above piping, the calculated ΔP curves were close enough to the experimental ones. The development of the hydraulic situation was not easy and included crucial points such as water flooding in different parts of above piping (in different experiments), co- and counter-flow of phases. The code simulated these processes very well.

2) The timing of predicted raise of cladding temperature (switch to the post-dryout mode) was detected earlier in ATHLET calculations. Implementation of different correlations had no effect because the change of parameters in FC in vicinity of transition to sub-critical heat transfer mode was rather fast. Thus the difference in correlations had no time to produce any real change in ATHLET calculations. In our opinion, the reason of the earlier overheating could be explained by local fluctuations of void fraction inside the fuel assembly. It should be noted that all of these processes take place in the area of very high void fractions and we did not intend to gather the minor effects just because one won't prove the conservatism of calculations when applied to real RBMK. The main task was to simulate the hydraulics of the processes, and ATHLET was successful in it.

3) Analyses of calculations allow us to suggest some ways of modeling regarding RBMK geometry:

   a) For the FC option of 5 balance equation model together with bundle drift option is suitable

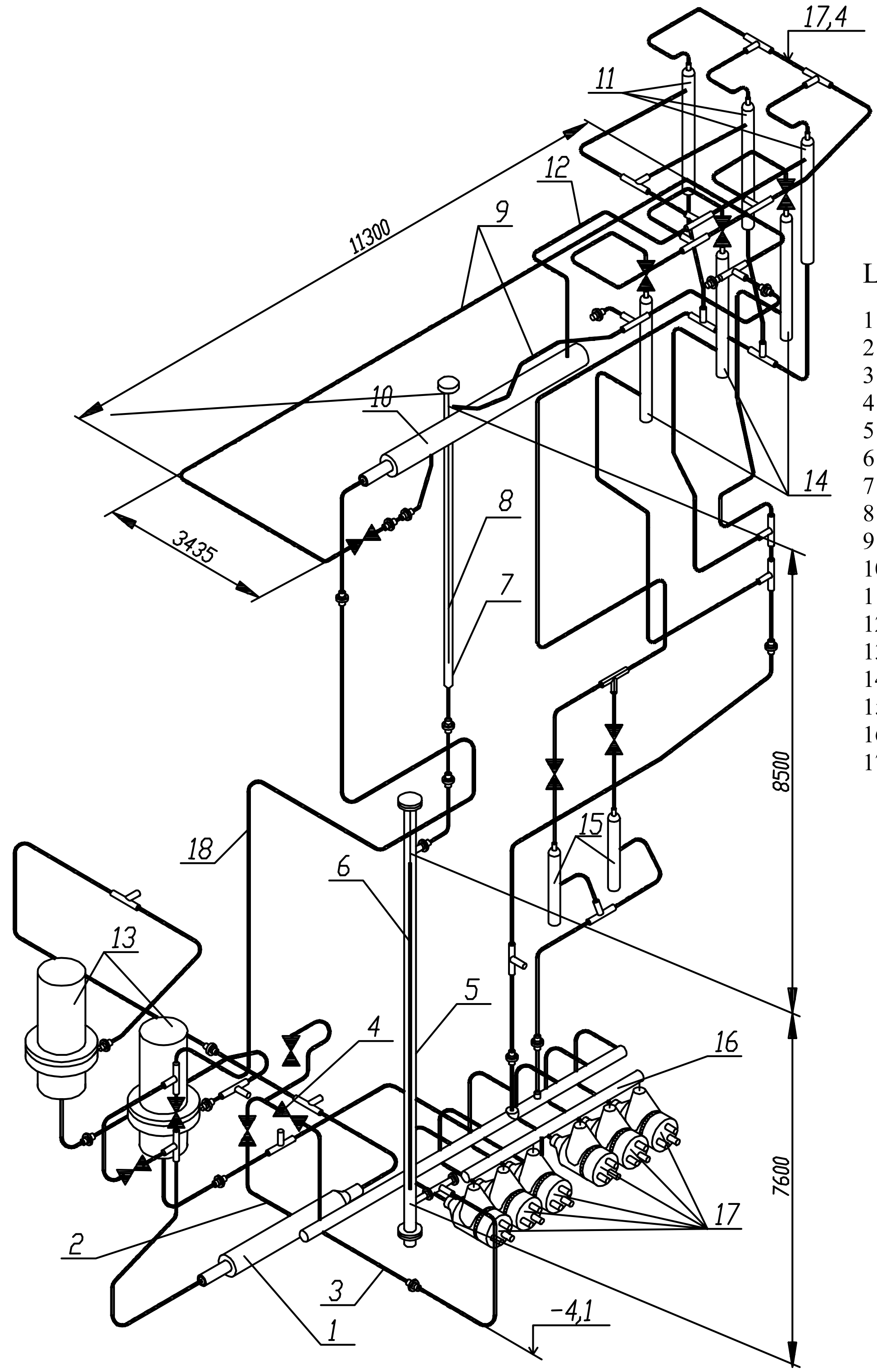
   b) For the riser and steam-water communications we recommend to use 6 balance equation model

7. References

1. KS experiments modeling the termination of fill flow at the entrance of the RBMK Fuel Channel conditioned by residual heat release. RRC "Kurchatov Institute", Moscow, 1997 (in Russian).

2. User's Manual "ATHLET Mod 1.2 Cycle A" Input Data description. 1988.

8. Figures



LEGEND:

1 – Pressure Header
2 – group distribution header
3 – low water feeding line
4 – isolating control valve
5 – fuel channel
6 – fuel assembly
7 – riser
8 – shield plug assembly
9 – steam water communication
10 – upper header
11 – separators
12 – line to separators
13 – circulation pumps
14 – second group of separators
15 – mixtures
16 – preheaters
17 – suction heder

Figure 2-1: KS Facility Layout.

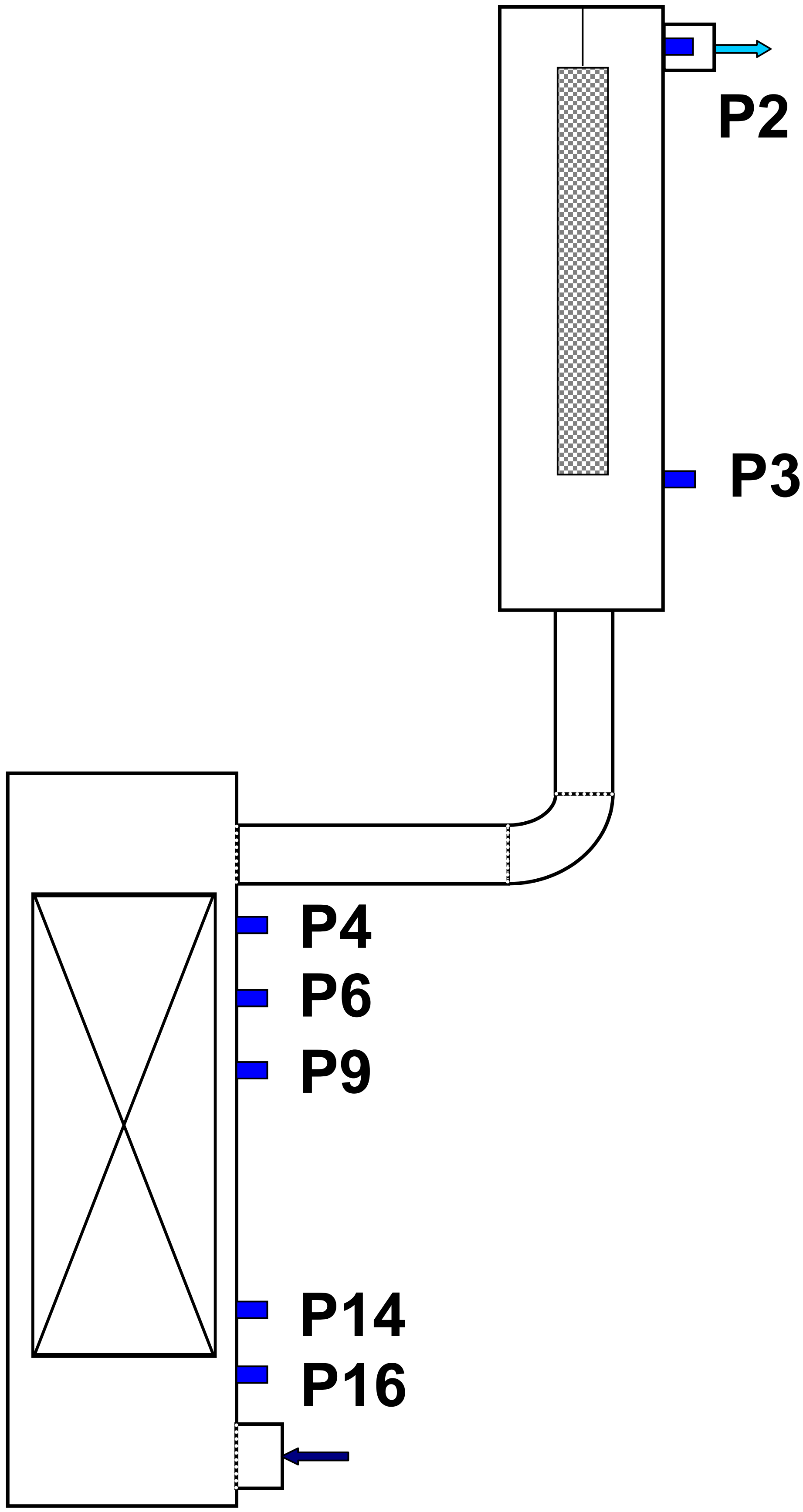


Figure 2-2: KS Facility Instrumentation

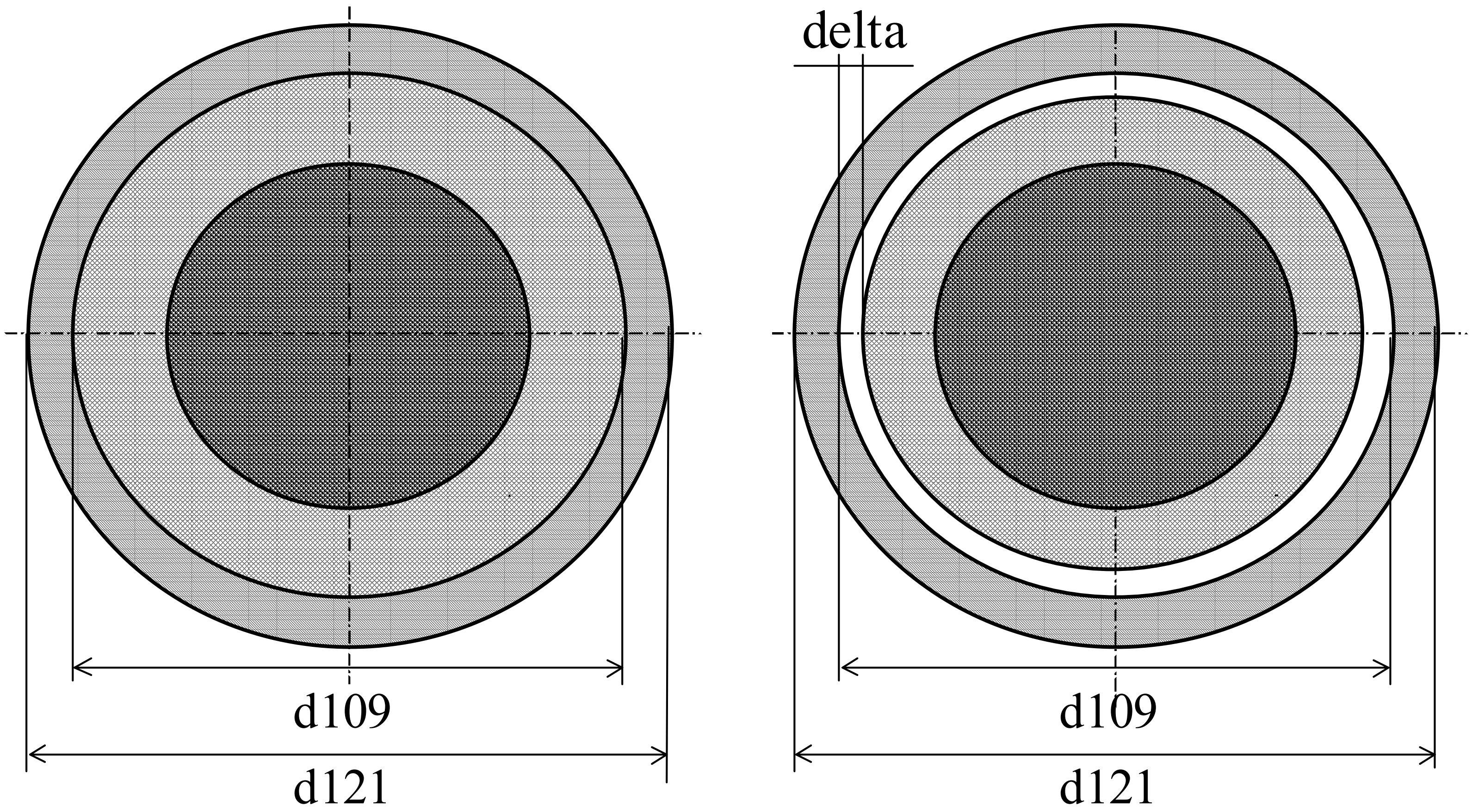


Figure 2-3:

Heated channel cross-section without- and with the gap between the tube and the insulation

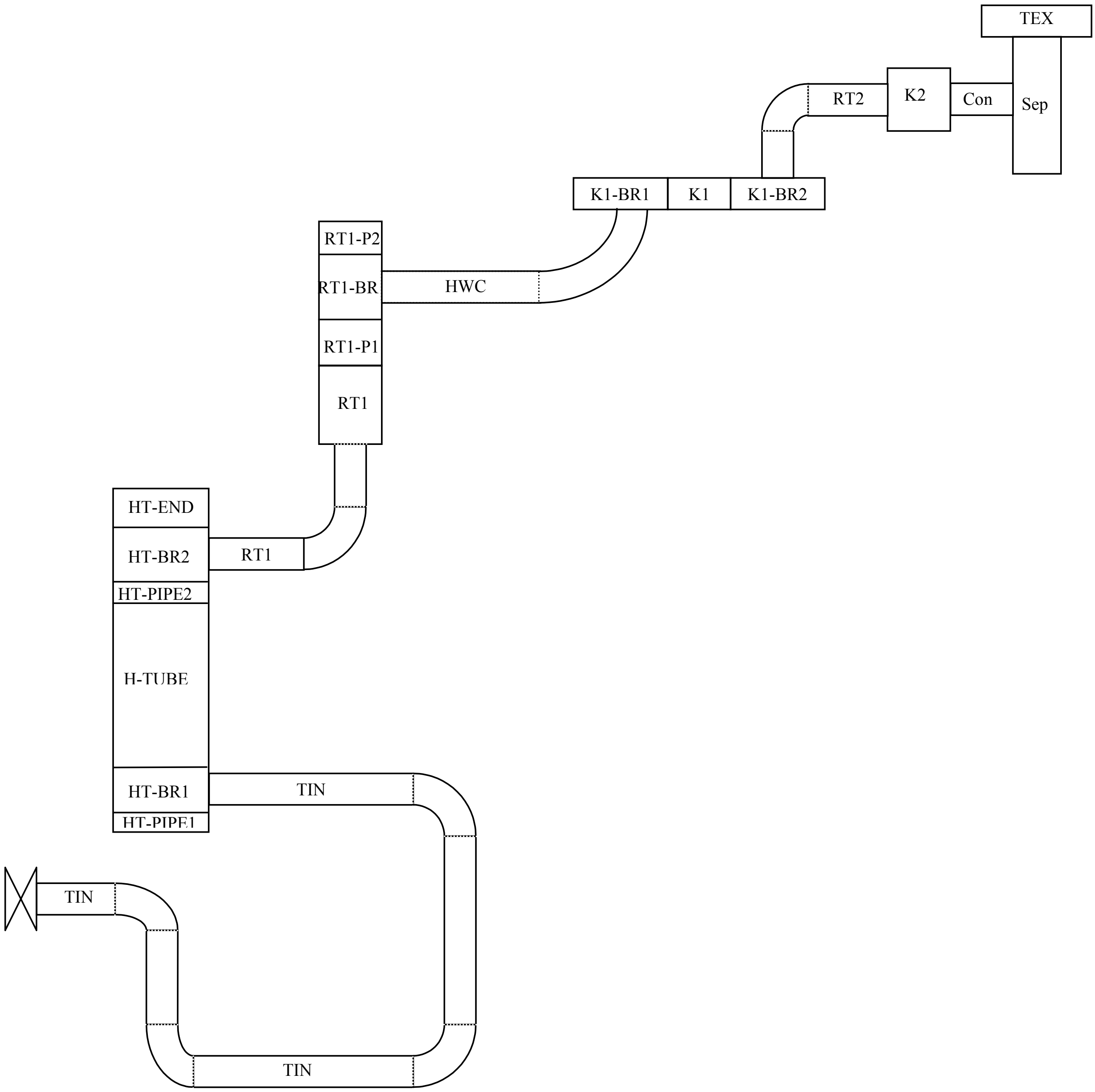


Figure 4-1: Nodalization scheme for One Channel Model.

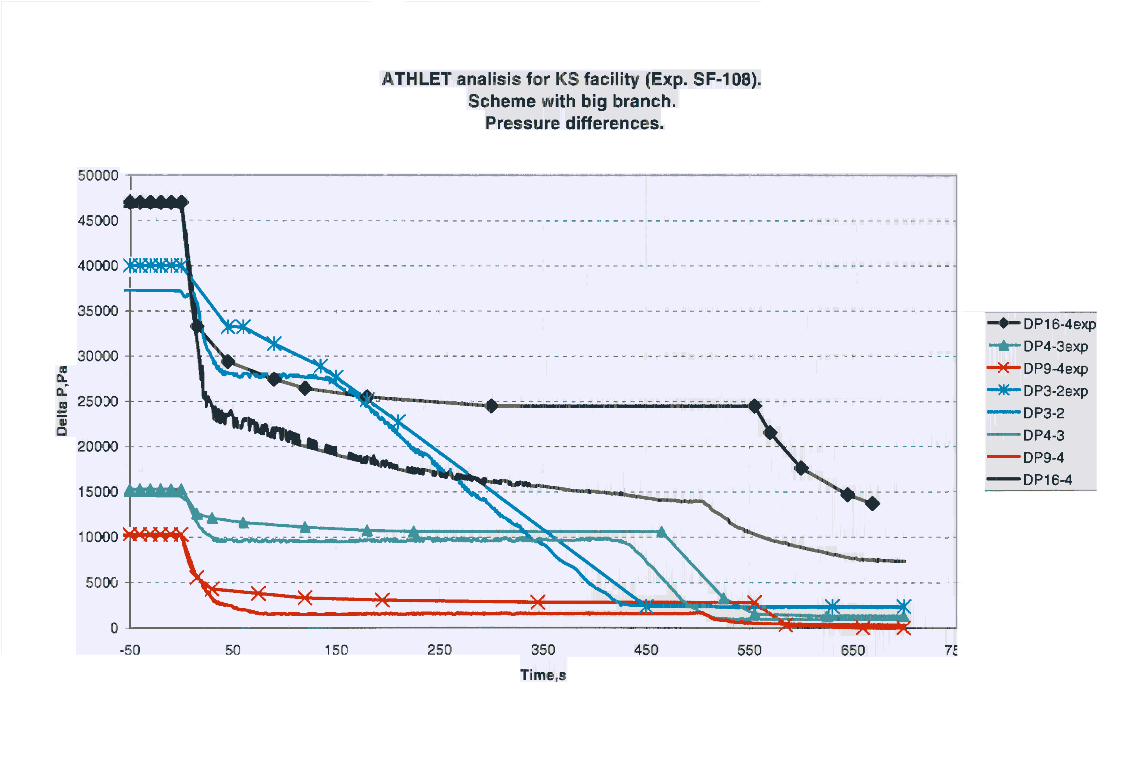


Figure 5.3-1: SF-108. Pressure differences (scheme with 1 CV for FC upper part).

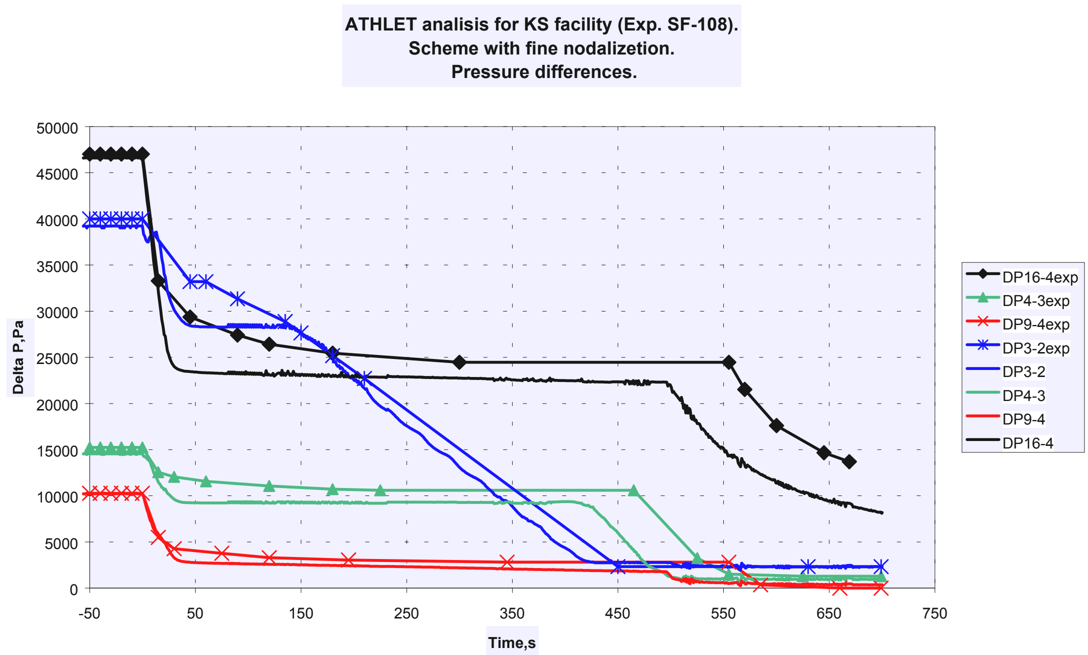


Figure 5.3-2: SF-108. Pressure differences (scheme with fine nodalization of FC upper part).

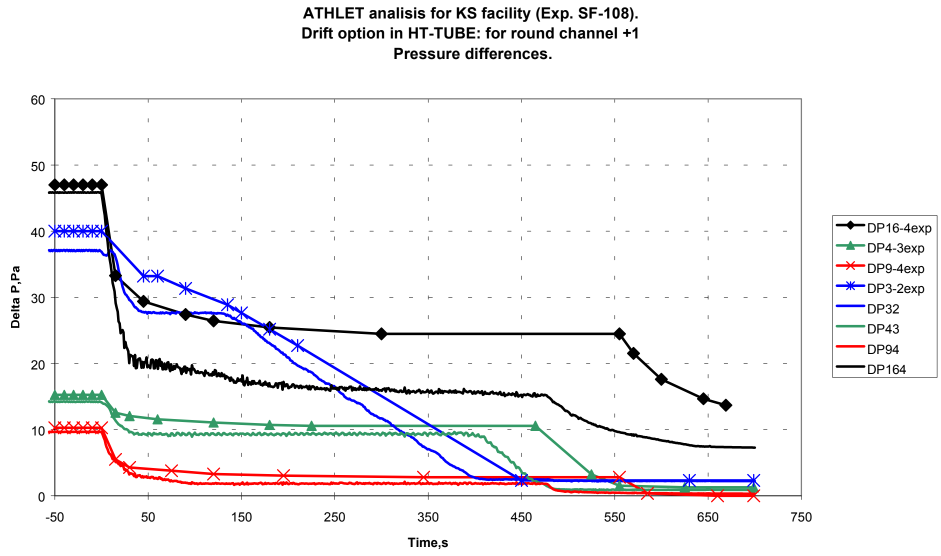


Figure 5.4-1: SF-108. Pressure differences (Drift option +1 in FC)

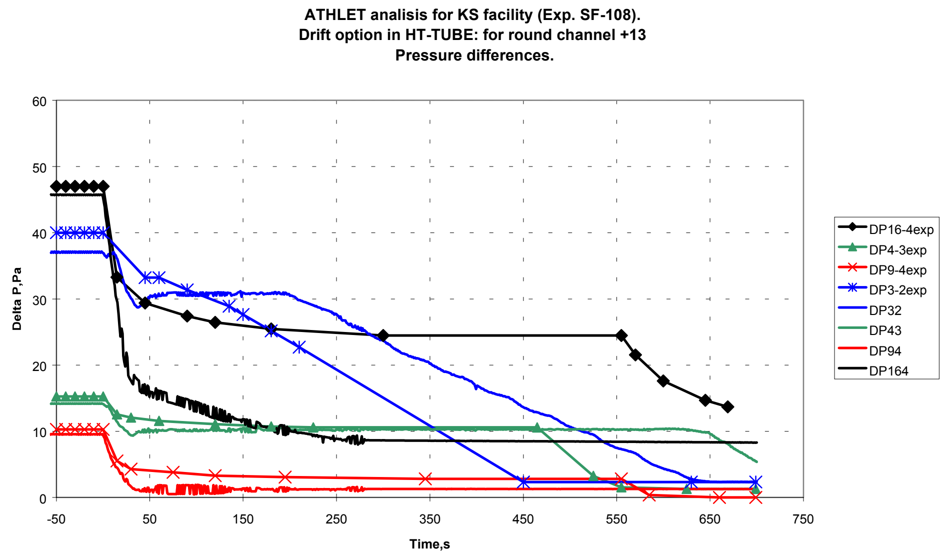


Figure 5.4-2: SF-108. Pressure differences (Drift option +13 in FC)

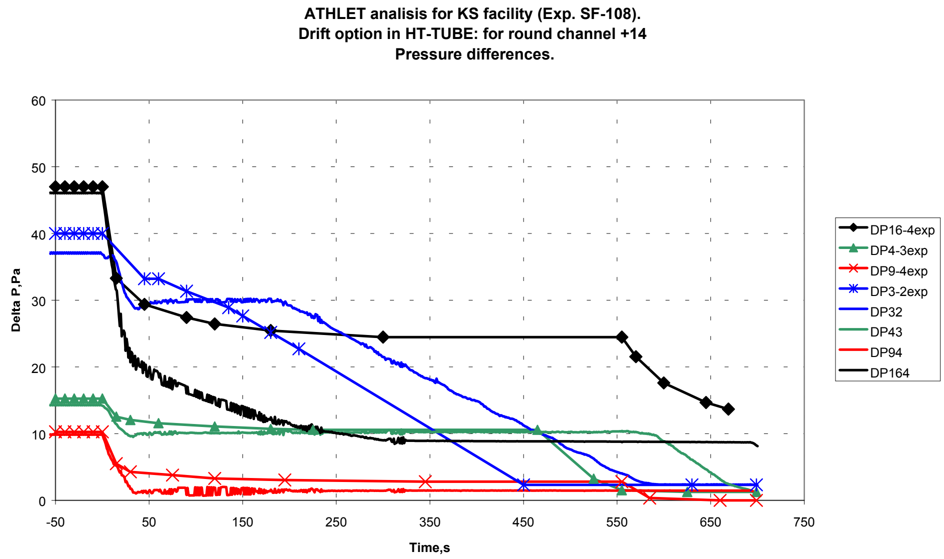


Figure 5.4-3: SF-108. Pressure differences (Drift option +14 in FC)

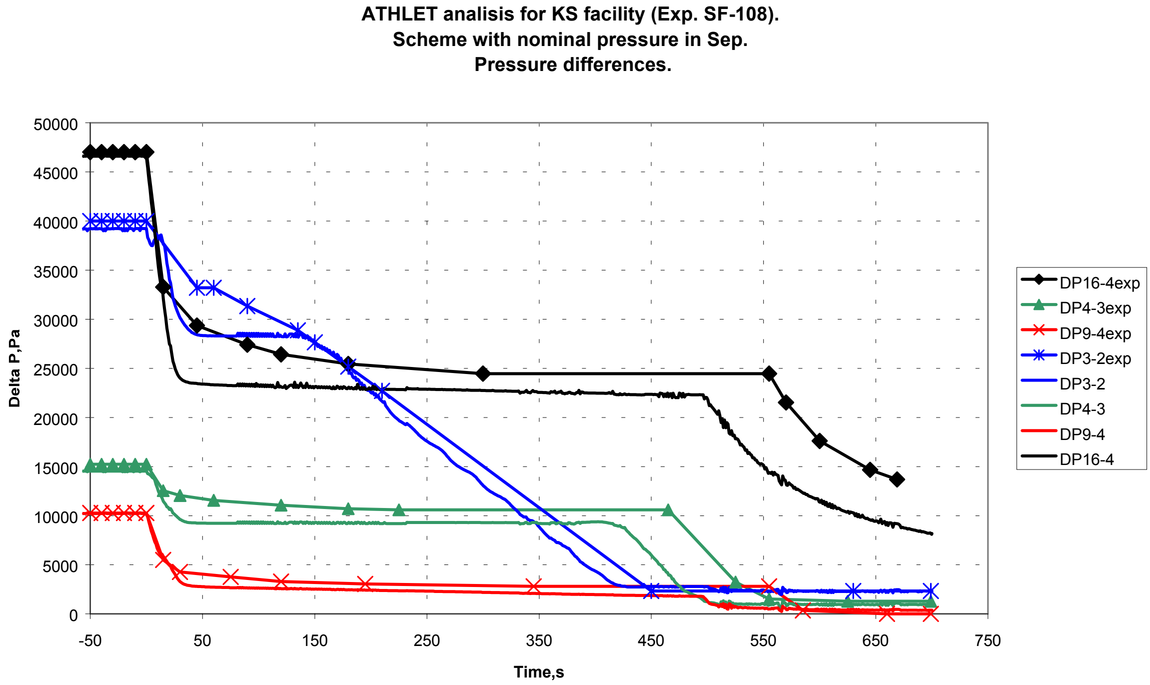


Figure 5.6-1: SF-108. Pressure differences (constant boundary pressure).

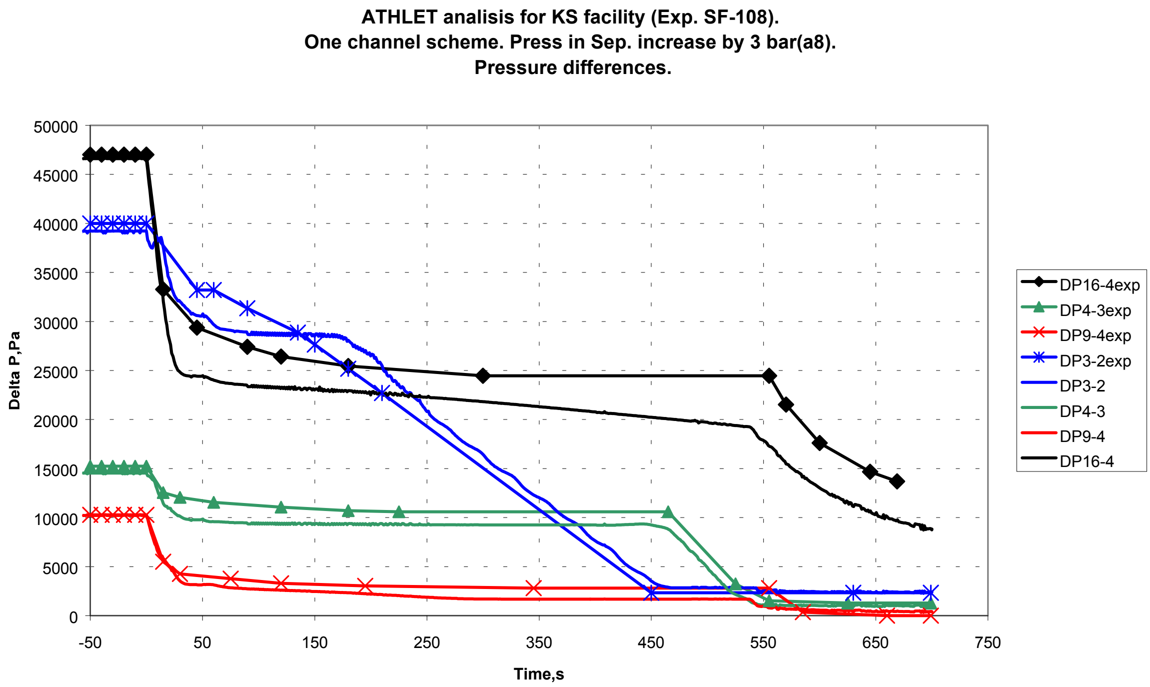


Figure 5.6-2: SF-108. Pressure differences (increased boundary pressure).

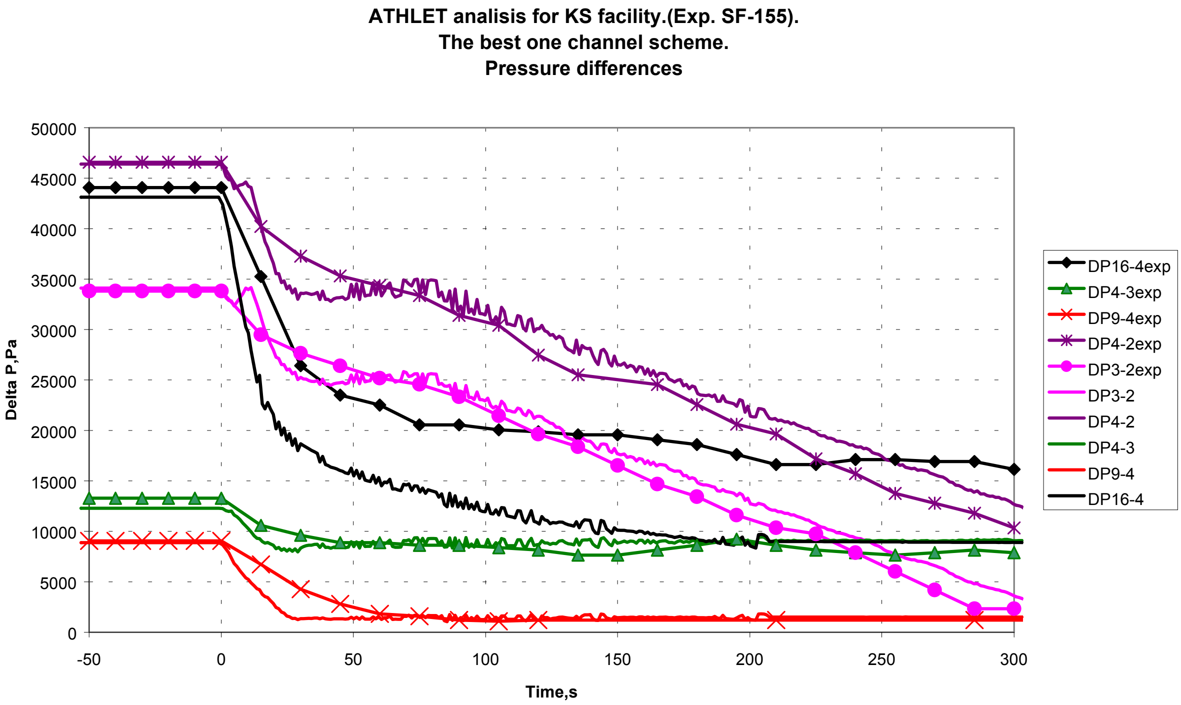


Figure 5.9-1: SF-155. Pressure differences (two-channel scheme).

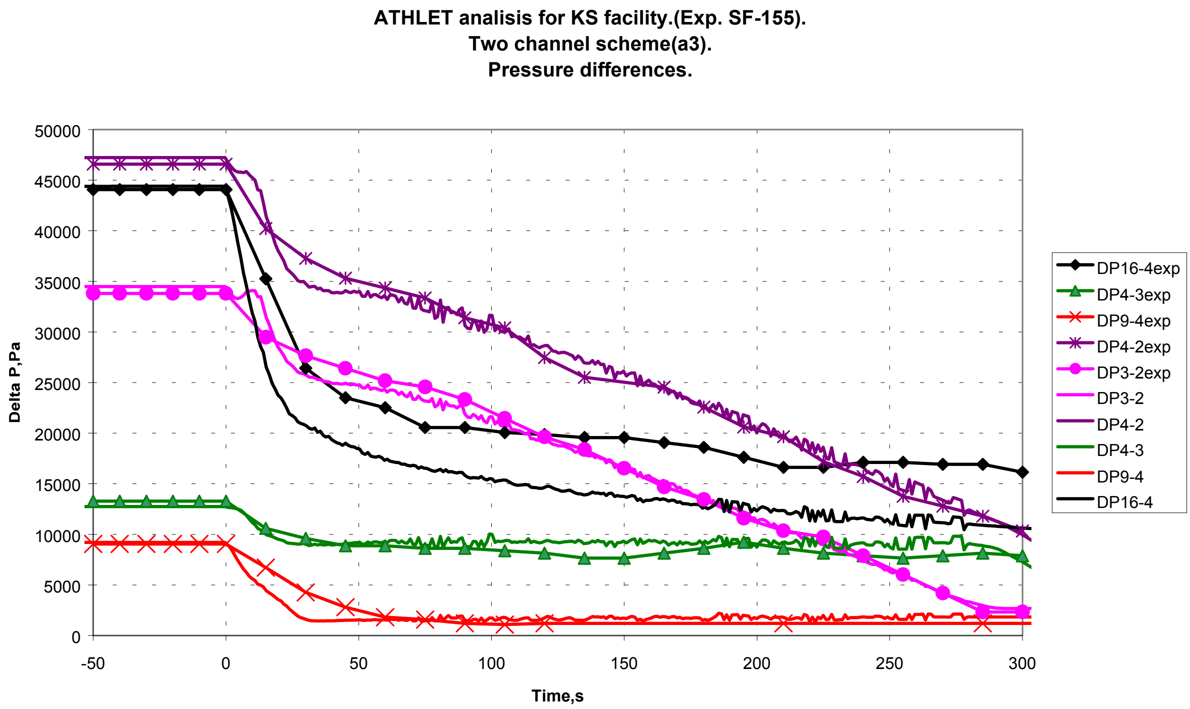


Figure 5.9-2: SF-155. Pressure differences (one-channel scheme).

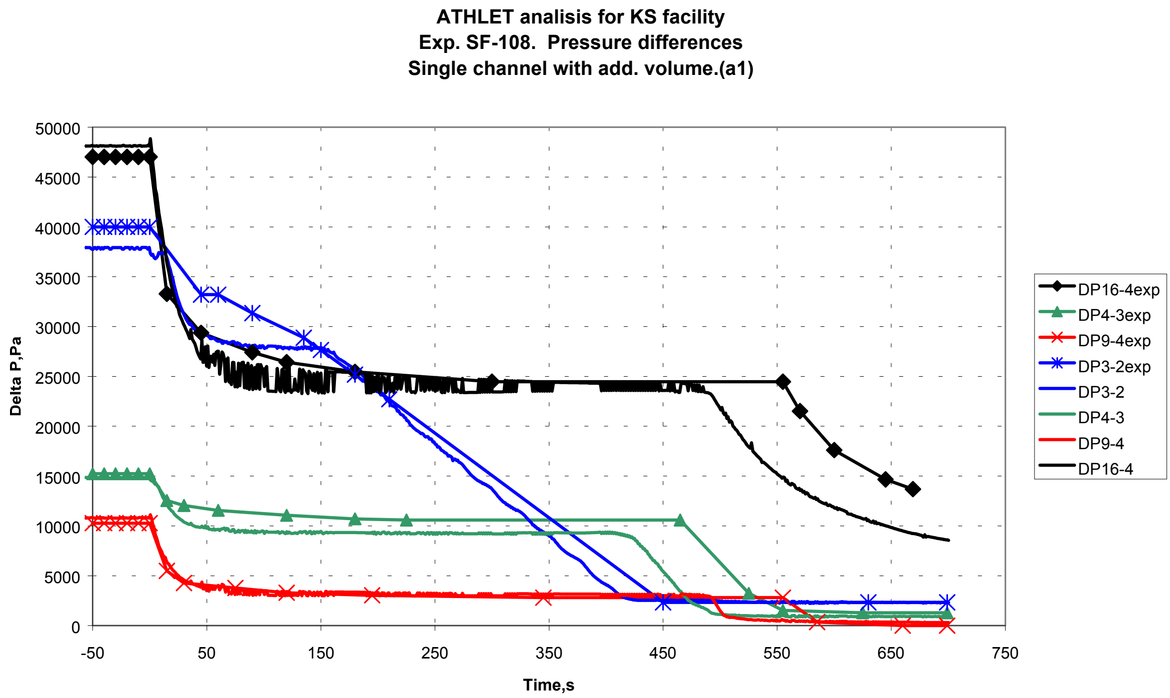


Figure 5.10-1: SF-108. Pressure differences (scheme with liquid path).

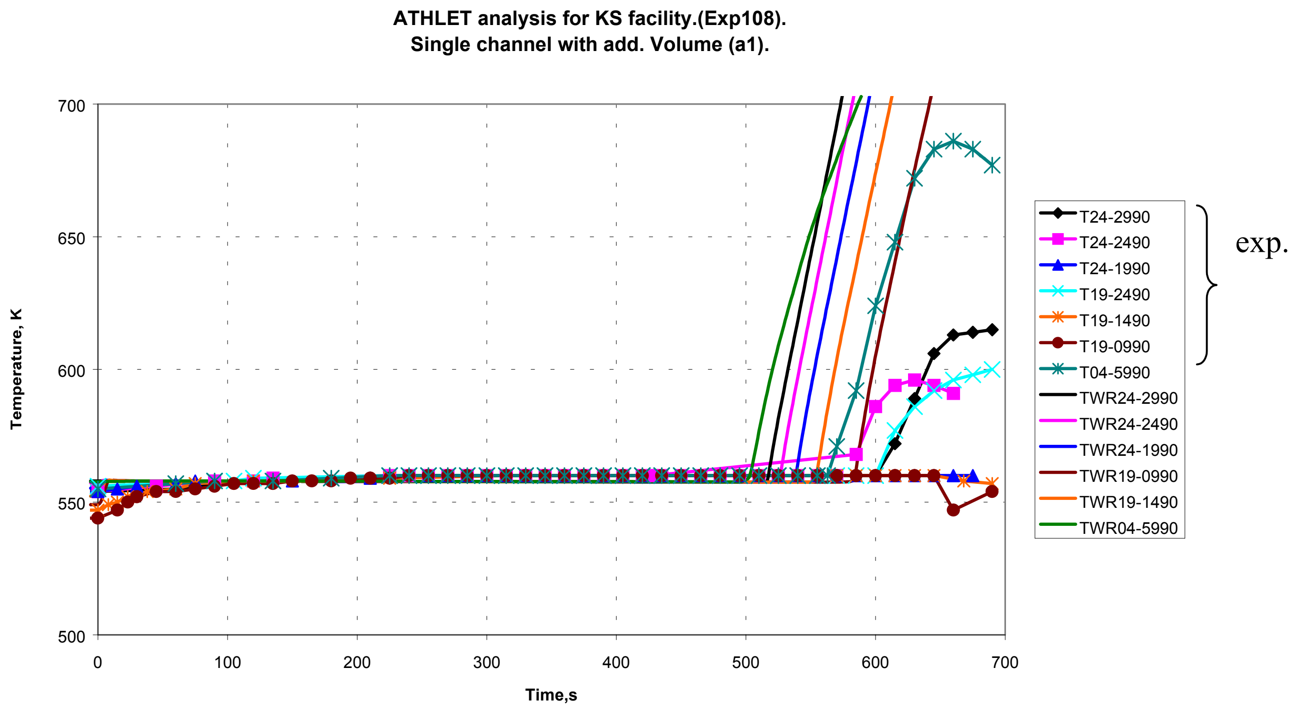


Figure 5.10-2: SF-108. Cladding temperature (scheme with liquid path).

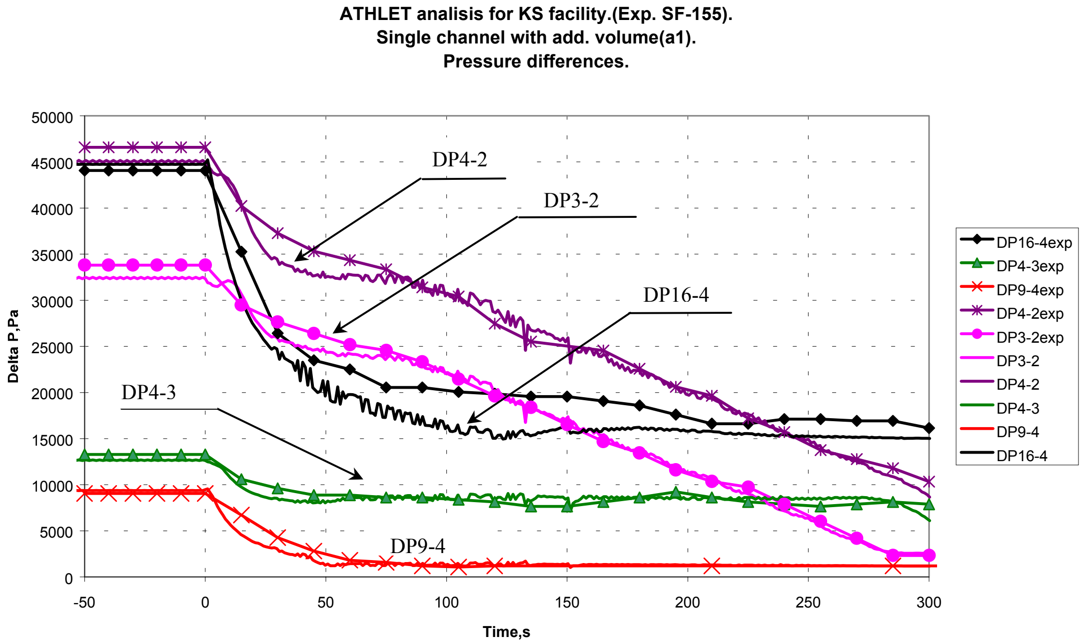


Figure 5.10-3: SF-155. Pressure differences (scheme with liquid path).

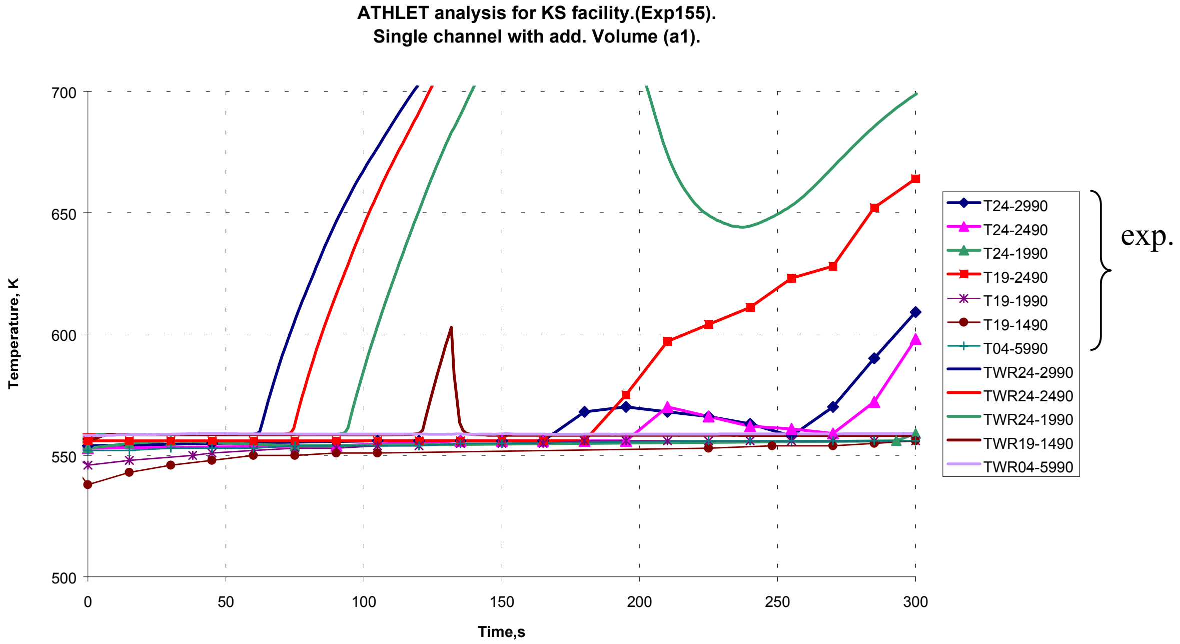


Figure 5.10-4: SF-155. Cladding temperature (scheme with liquid path).

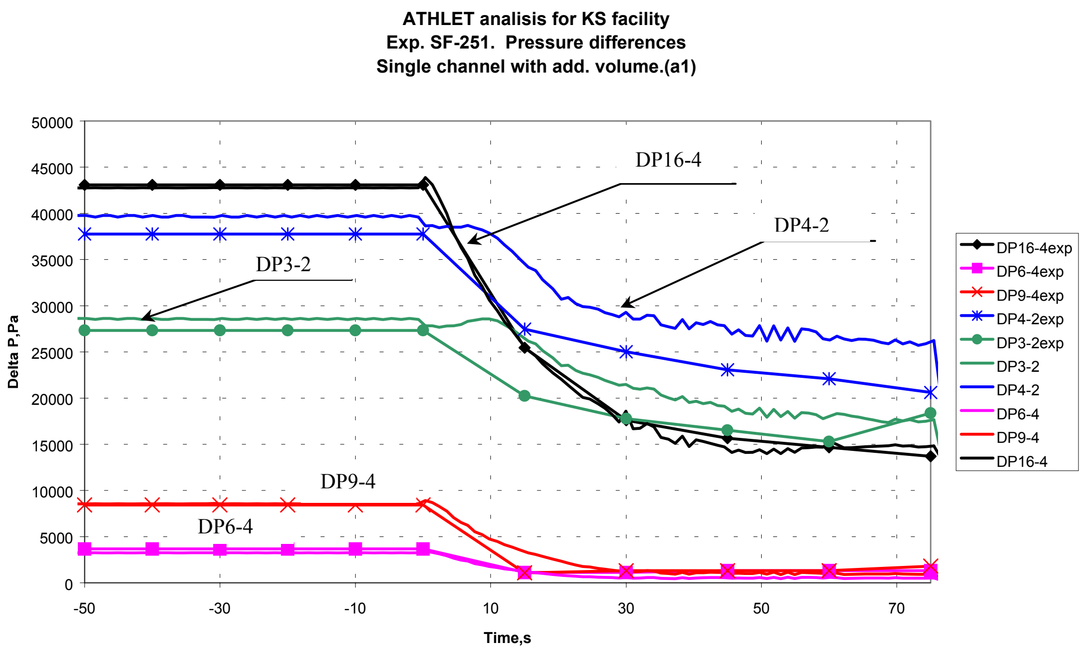
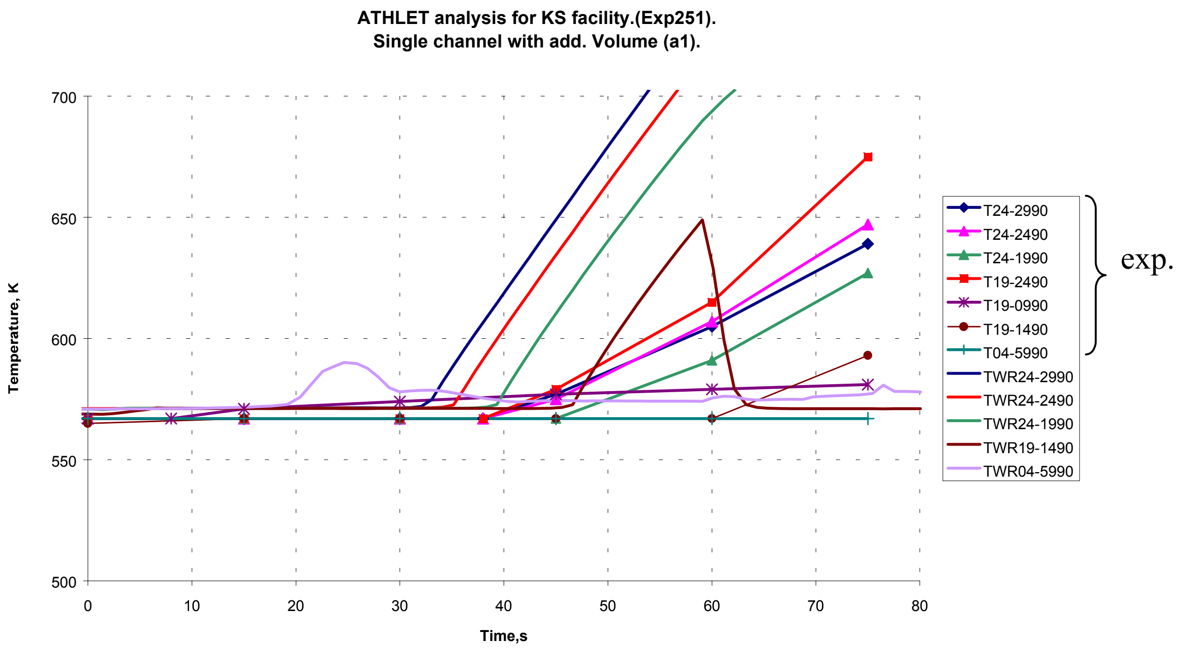


Figure 5.10-5: SF-251. Pressure differences (scheme with liquid path).



9. **Figure 5.10-6: SF-251. Cladding temperature (scheme with liquid path).**